BACKGROUND

Aspects of the present invention relate to the monitoring and control of a substrate fabrication process.

Advances in electronic circuit technologies are requiring substrate features to have increasingly smaller or finer sizes, such as thinner interconnect lines and higher aspect ratios vias. Typically, the substrate is a semiconductor or dielectric substratum, that is processed to form features composed of dielectric, semiconducting and conducting materials, on the substrate. Small sized features allow packing of larger numbers of features into smaller areas and their operation at higher frequencies. For example, metal-containing interconnect lines are often being sized less than about 0.18 nm, and sometimes, even less than about 0.15 nm. However, it becomes increasingly difficult to fabricate such features with consistent dimensions and shapes across the substrate surface, especially as the features become ever smaller in size. In such fabrication process, unpredictable variations in process variables across the substrate surface can form features having different dimensions at different regions of the substrate surface. This makes it difficult to properly design a circuit or display, since the electrical or other properties of the features randomly vary across the substrate surface.

The problem of fabricating the fine features is all the more difficult when the features have tolerance ranges that are much smaller than those of conventional features. Variations in feature size or shape across the substrate that were previously acceptable for larger sized conventional features are longer no acceptable for the fine features. Feature shape variability is especially a problem when the critical dimensions of the features are those that vary across the substrate surface. The critical dimensions are those dimensions that significantly affect the electrical properties of the features. For example, the line width of interconnect lines is a critical dimension, because when a portion of an interconnect line is over-etched, the excessively thin portion has a higher resistance. Even a small change in dimension or sidewall taper angle of such an interconnect feature can result in out of tolerance electrical properties. As a result, many circuits having finely sized features are rejected for not meeting dimensional tolerance ranges as compared to conventional circuits.

Thus, it is desirable to be able to form finely sized features on a substrate that have consistent shapes and dimensions. It is further desirable to ensure that the features have uniform critical dimensions irrespective of their location on the substrate surface. It is also desirable to etch ultra fine features with good processing throughout and high yields.

SUMMARY

In one aspect of the invention, a substrate processing apparatus has a process chamber having a substrate support to receive a substrate, the substrate having first and second regions, a gas distributor to introduce a gas into the chamber, a gas energizer to energize the gas to form features on the substrate, and a gas exhaust port to exhaust the gas. The apparatus also has a process monitor to monitor a dimension of a pattern of spaced apart and discrete features being formed in the first region of the substrate and generate a first signal, and monitor a dimension of a pattern of spaced apart and discrete features being formed in the second region of the substrate and generate a second signal. The apparatus further has a chamber controller to receive the first and second signals and operate the substrate support, gas distributor, gas energizer, or gas exhaust port, to set process parameters including one or more of a gas flow rate, gas pressure, gas energizing power level, and substrate temperature, to process the features in the first and second regions to compensate for any differences in the dimensions of the features being formed in the first and second regions.

A version of a method of processing a substrate includes placing a substrate in a process zone, the substrate having first and second regions, introducing a process gas into the process zone, energizing the process gas to form a pattern of spaced apart and discrete features on the substrate and exhausting the process gas. A dimension of a pattern of spaced apart and discrete features being formed in the first region of the substrate is monitored and a first signal is generated. A dimension of a pattern of spaced apart and discrete features being formed in the second region of the substrate is also monitored and a second signal is generated. The first and second signals are evaluated and process parameters in the process zone are set to process the features in the first and second regions to compensate for any differences in the dimensions of the features, the process parameters including one or more of a gas flow rate, gas pressure, gas energizing power level, and substrate temperature.

In another aspect of the invention, a substrate etching apparatus has an etching chamber having a substrate support to receive a substrate, the substrate having a central region exposed to a first processing sector of the chamber and a peripheral region exposed to a second processing sector of the chamber, a gas distributor to

introduce an etching gas into the chamber, a gas energizer to energize the etching gas to etch features on the substrate, and a gas exhaust port to exhaust the etching gas. The substrate etching apparatus also has a first light detector to detect light reflected from features being etched at the central region of the substrate and generate a first signal proportional to a measured dimension of the features, and a second light detector to detect light reflected from features being etched at the peripheral region of the substrate and generate a second signal proportional to a measured dimension of the features. A chamber controller receives and evaluates the first and second signals and operates the etching chamber to set a process parameter at a controllable first level in the first processing sector, the first level being selected in relation to the first signal, and the process parameter at a controllable second level in the second processing sector, the second level being selected in relation to the second signal, thereby providing independent monitoring and control of the dimensions of the features being etched at the central and peripheral regions of the substrate.

A version of a substrate etching method includes placing a substrate in a process zone, the substrate having a central region exposed to a first processing sector of the chamber and a peripheral region exposed to a second processing sector of the chamber, introducing an etching gas into the process zone, energizing the etching gas to etch features on the substrate, and exhausting the etching gas. Light reflected from features being etched at the central region of the substrate is detected and a first signal proportional to a critical dimension of the features is generated. Light reflected from features being etched at the peripheral region of the substrate is also detected and a second signal proportional to a critical dimension of the second features is generated. The first and second signals are evaluated and the chamber is operated to set a process parameter at a controllable first level in the first processing sector, the first level being selected in relation to the first signal, and the process parameter at a controllable second level in a second processing sector, the second level being selected in relation to the second signal, thereby providing independent monitoring and control of the critical dimensions of the features at the central and peripheral regions of the substrate.

In yet another aspect, a substrate etching apparatus has a chamber having a substrate support to receive a substrate, the substrate having first and second regions, a gas distributor to introduce an etching gas into the chamber, a gas energizer to energize the etching gas to etch features in the substrate, and a gas exhaust port to

exhaust the etching gas. The etching apparatus also has a first light detector to detect light reflected from features in the first region of the substrate and generate a first signal proportional to a dimension of the features, and a second light detector to detect light reflected from the second region of the substrate and generate a second signal proportional to a dimension of the features. A chamber controller evaluates the first and second signals and selects an etching process recipe in relation to the first and second signals, and operates the chamber according to the etching process recipe, whereby the etching of the features at the first and second regions is independently monitored and controlled.

Another method of etching a substrate includes placing a substrate in a process zone, the substrate having first and second regions, introducing an etching gas into the process zone, energizing the etching gas to etch features on the substrate, and exhausting the etching gas. Light reflected from features in the first region of the substrate is detected and a first signal is generated. Light reflected from features in the second region of the substrate is also detected and a second signal is generated. The first and second signals are evaluated and an etching process recipe is selected in relation to the first and second signals. Process parameters in the chamber are set according to the etching process recipe, whereby etching of the features at the first and second regions is independently monitored and controlled.

DRAWINGS

These features, aspects, and advantages of the present invention will become better understood with regard to the following description, appended claims, and accompanying drawings which illustrate exemplary features of the invention:

Figure 1a is a schematic sectional top view of a substrate processing apparatus showing a platform with load-lock chambers, process chambers, and a measurement chamber;

Figure 1b is a sectional side view of a process chamber having a process monitor and a chamber controller;

Figure 1c is a sectional side view of a portion of a chamber having a gas energizer comprising an antenna and a centrally located process monitor on the ceiling;

Figure 1d is a schematic sectional side view of a portion of a process chamber having a substrate to be processed showing similar features in different regions of the substrate;

Figure 1e is a bottom view of the gas distributor of Figure 1c showing concentric central and peripheral gas outlets;

Figure 1f is a schematic diagram of the magnetic field generator of the chamber of Figure 1b;

Figure 1g is a schematic diagram of another embodiment of a magnetic field generator suitable for the chamber of Figure 1b;

Figure 1h is a schematic diagram of a side view of substrate support having dual heat transfer gas pressure zones;

Figure 1i is a schematic diagram of a top view of the substrate support of Figure 1h;

Figure 2a is a schematic diagram of an embodiment of a chamber controller suitable for operating the process chambers of Figures 1a-1d;

Figure 2b is an illustrative block diagram of the hierarchical control structure of a computer readable program of the chamber controller of Figure 2a;

Figure 3 is a graph of plots showing control of etching rates of features at different regions across a substrate by regulating process gas flow though central, peripheral, or both gas outlets;

Figure 4 is a graph of plots showing the relative etch rate uniformity achieved when etching gas is passed through only one or both of the central and peripheral gas outlets at different gas flow valve opening sizes;

Figure 5 is a graph of plots showing control of the variation of taper angles of etched features across the substrate by regulating the opening size of the central and peripheral gas outlets (0 is closed to 1 fully open peripheral gas outlet);

Figure 6 is a graph of plots of the taper angle uniformity at different flow rates of etching gas passed through peripheral and central gas outlets for isolated and dense features;

Figure 7 shows the variation in feature taper angle from the center to a substrate perimeter for different etching gas compositions;

Figures 8a-c are graphs plotting magnetic field strength produced by the magnetic field generator of Figure 1g, as a function of radial position above the substrate;

Figure 9 is a graph of plots showing the variations in etching rates at the central and peripheral regions of the substrate achieved for different magnetic field strengths;

Figure 10 is a graph of plots showing the variation in feature etch rates obtained by adjusting the source power levels of the current applied to an inductor antenna; and

Figure 11 is a schematic diagram of a metrology tool to measure the dimensions of the features being processed on the substrate.

DESCRIPTION

According to an exemplary embodiment, a substrate processing apparatus **100**, as illustrated in Figures 1a-d, includes a process chamber **104a-c** for processing a substrate **102** and a process monitor **180** to monitor features **85** at different locations on substrate **102**. The apparatus **100** is useful for processing substrates, such as semiconductor wafers and displays, is provided to illustrate the invention; however, it should not be used to limit the scope of the invention or its equivalents. Generally, the apparatus **100** comprises a platform **101** having electrical connections and plumbing for load lock chambers **103a,b**, substrate processing chambers **104a-c**, and a measurement chamber **105**, as is illustrated in Figure 1a. The load lock chambers **103a,b** are provided to receive cassettes containing batches of substrates **102**. The substrates **102** are transferred from the load lock chambers **103a,b** to the substrate processing chambers **104a-c** by a robot arm **107**. The substrates **102** are successively processed in the processing chambers **104-c**, which may be, for example, etching, deposition, annealing, or cleaning chambers. The measurement chamber **105** is used to make measurements on individual substrates from a batch of substrates, such as for example, the first or initial substrate from the batch. While different chambers are described, the apparatus **100** is not limited to a particular set or arrangement of chambers and may have only a single chamber.

The process chamber **104a** has enclosure walls comprising a ceiling **106**, sidewall **108**, and bottom wall **110**, that define a processing sector **112** to maintain an energized gas about the substrate **102**, as shown in Figure 1b. The ceiling **106** or sidewalls **108** of the chamber **104** can have one or more windows **113a,b** that allow radiation, such as light, to pass through. A substrate support **114** has a substrate receiving surface **116** to receive a substrate **102** transported into the processing sector **112** by the robot arm **107**. In one version, the support **114** comprises a dielectric **118** that at least partially covers an electrode **120** that is chargeable to generate an electrostatic charge to electrostatically hold the substrate **102**. A heat transfer gas supply **121** may be used to provide a heat transfer gas such as helium to the backside of the substrate **102.**

Process gas, such as for example, an etching gas capable of etching material on the substrate **102**, is introduced into the chamber **104** through a gas distributor **122**. The chamber **104** also comprises a gas exhaust **156** to exhaust gas from the chamber **104** and to set a pressure of the gas in the chamber **104**. The exhaust **156** comprises an exhaust port **158** about the substrate support **114** that leads to an exhaust line **162** that conveys the gas to the exhaust pumps **164**. A throttle valve **163** in the exhaust line **162** controls the flow of gas out of the chamber **104**. The pumps **164** typically include roughing and high vacuum-type pumps.

A gas energizer **165** couples RF or microwave energy to the process gas to energize the gas in the processing sector **112** of the chamber **104** or in a remote zone (not shown) outside the chamber **104**. In one version, the gas energizer **165** comprises a pair of electrodes, with one electrode **120** being in the support **114** and the other being formed by the sidewall **108** or ceiling **106** of the chamber **104**. An electrode power supply **166** applies an RF power to the electrode **120** via an RF power supply 169 and RF match network **168** while the walls **106, 108** are maintained at a ground or floating potentials; and optionally, a DC voltage supply **167** is provided to apply a DC voltage to the electrode **120** to generate electrostatic charge to hold the substrate **102**. In another version, the gas energizer **165** comprises antenna **174** that is powered by an antenna power supply **175** via an RF match network **177**, as shown in Figure 1c. The antenna **174** may comprise inductor coils **179a,b** that cover the ceiling **106** of the chamber **104** and generate an induction field in the chamber **104** to energize the gas in the chamber. In this chamber **104**, the ceiling **106** is made from a dielectric material such as aluminum oxide, to allow inductive energy from the antenna to permeate therethrough; and can also be made of a semiconductor material, such as silicon, to serve as an electrode that couples to the electrode **120** in the chamber **104**. The gas energizer **165** can also be both an electrode **120** and an antenna **174** that are used together. Optionally, the chamber **104** can also comprise a magnetic field generator **170**, as shown in Figure 1f, to shape, mix or confine the energized gas, as further described herein.

The process monitor **180** is set up to monitor a dimension of features **85** in a first region **144** of the substrate **102** and generate a first signal, and to monitor a dimension of features **85** in a second region **146** of the substrate **102** and generate a

second signal. The features **85** are discrete structures that are separated from one another by distinct spaces, such as raised mesas or troughs in the substrate **102**, which are arranged in a repetitive pattern to form an array of the feature structures, for example as schematically illustrated in Figure 1d. The measured feature dimensions include a width, depth, opening size, or taper angle of each feature **85**. For example, the measurable dimensions of features **85** such as vias or contact holes can be an opening size, depth or aspect ratio. The measurable dimension of an interconnect lines is typically the line width, height, or thickness of the feature. Typically, each measurement represents an average value for a small number of individual separate features **85**, but the measurements can also be of individual single features **85**. Other discrete features **85**, such as n or p-doped sites can also be measured in terms of dopant concentration levels, type, or coverage area.

The dimensions of the features **85** being formed on the substrate **102** are monitored at least two different locations **144, 146** on the substrate **102**. The measurement locations across the substrate **102** can be chosen, for example, in relation to the variations that are empirically determined by processing test substrates **102** to determine where features variations occurred across the substrate **102**. For example, in certain etching processes, when features **85** etched at a first central region **144** of the substrate **102** are found to have a different shape than the features **85** etched in a second peripheral region **146** of the substrate **102** from the actual measurements of processed substrates, the process monitor **180** is set up to measure the dimensions of the features **85** at the central and peripheral location **144, 146** of the substrate **102**. However, the measurements may also be made at other positions across the substrate **102**, for example, at opposing edges of the substrate, such as substrate edges that lie near gas ingress or and egress points in the chamber **104**. The process monitor **180** can also be adapted to measure features **85** at multiple grid points across the substrate **102**, such as at the intersection points of a grid comprising horizontal and vertical lines that covers the area of the substrate **102**. Locations with similar attributes, for example, a series of locations about, for example, the periphery of the substrate **102** can also be measured and the signals averaged to generate a single signal, such as for example, for the annular region abutting the substrate periphery.

The signals generated by the process monitor **180** are sent to a chamber controller **300** that operates the chamber **104** to form a closed control loop capable of adjusting processing conditions in the chamber **104** in response to the signals from the process monitor **180**. The chamber controller **300** receives the feature dimension signals from the process monitor **180**, evaluates them, and sends control signals to operate the chamber **104** to set process conditions in the chamber **104a,b** to achieve desired feature attributes across the substrate **102**, such as a controlled or improved dimensional uniformity of the features **85** being formed at different regions across the substrate **102**. In the signal evaluation process, the chamber controller **300** can determine appropriate process conditions in the chamber **104a,b** from a look-up table or by mathematically computing the desirable process conditions from the first and second signal levels received from the process monitor **180**.

In one embodiment, the chamber controller **300** operates the chamber components to set process parameters to different levels at different processing sectors **136, 138** within a process zone **112** of a chamber **104** directly in relation to the magnitude of the feature measurement signals. The process conditions within processing sectors **136, 138** determine how features **85** in that particular region of the substrate **102** are processed. For example, the chamber controller **300** can receive the first and second signals and set process parameters in the chamber **104a,b** that process the features **85** in the first and second regions to compensate for any differences in the dimensions of the features **85**. The processing sectors **136, 138** are adjacent portions of the process zone **112** in which different processing conditions may be set. For example, a first processing sector **136** can be located above a first region **144** of the substrate **102** and a second processing sector **138** can be located above a second region **146** that is concentric to, and radially outward of, the first region **144**. In this version, the first region **144** is a central portion and the second region **146** is a peripheral portion of the substrate **102**. As another example, the first region **144** can be located near a gas ingress point in the chamber **104a,b**, such as about outlets **142** of the gas distributor **122**, and the second region **144** located about a gas egress point, such as about a gas exhaust port **158**.

In each processing sector, the chamber controller sets a selected process parameter at a particular level. The localized levels of the process parameters within

the smaller processing sectors **136, 138,** can be independently set to discrete or different values to control processing attributes of the features **85** of the substrate **102** exposed to the energized gas in the particular processing sector **136, 138**. For example, a localized process parameter can comprise a gas flow rate or velocity; a substrate temperature of a region of the substrate **102** located within the bounds of the sector, such as an inner or outer annular region of a substrate **102**; a gas energizing power level applied to the gas energizer **165** that can independently energized the gas at a particular level in the sector relative to other sectors; or an average magnetic field strength within a sector in the chamber **104**. By setting the process parameters at different levels in each processing sectors **136, 138**, the processing of features **85** at different regions **144, 146** of the substrate **102** can be independently controlled to maintain predefined first and second processing rates or to achieve pre-selected levels of processing. For example, processing of the features **85** can be controlled so that the features **85** at different regions **144, 146** across the substrate **102** over the course of processing develop substantially the same dimensions or achieve desirable levels of differences in attributes. For example, the chamber controller **300** can set the localized process parameter at a controllable first level in the first processing sector **136** in the chamber **104a,b** to process the features **85** in the first region **144** of the substrate **102** at a first processing rate, and to simultaneously process the features **85** in the second region **146** at a second processing rate by setting the localized process parameter at a controllable second level in the second processing sector **138**, such that the features **85** end up with the same dimensions, or a defined difference in dimensions, at the termination of processing.

In another embodiment, the chamber controller **300** selects a particular process recipe from a stored look-up table which contains a plurality of process recipes. The selected process recipe corresponds to particular sets of first and second signal levels detected by the process monitor **180** for the dimensions of the features **85** at the different substrate regions **144, 146**. Each process recipe can be tailored to equalize process characteristics at the two measurement regions **144, 146** so that features **85** are etched to have substantially the same dimensions or a controlled difference in dimensions. Each recipe can include particular predefined levels of substrate temperature, gas composition, gas flow rates through different gas outlets, gas energizer power levels, or magnetic field strengths. In one version, for example, the

process recipe uses a gas composition that increases processing rates of the features **85** at the first region **144** of the substrate **102** over the other region **146** to equalize processing rates at the termination of the process. The look-up table has sets of first and second signal levels, or a mathematical operand of the first and second signals, that are associated with a process recipe containing a set of process parameter levels. For example, each table entry may be an ordered set of numbers, the first two numbers being values of the first and second signal levels and the third number being the number of an associated process recipe. In another example, the look-up table may contain an ordered set comprising a first number that is a mathematical operand of the first and second signals, e.g., the ratio of the first signal and second signal levels, the difference between the first and second signal levels, or some other algebraic relationship between the first and second signal levels; and the second being the associated process recipe number that contains a set of process parameter levels.

A process recipe may also be selected based on measurements of a single substrate **102** from a batch of substrates that are being processed. For example, when a cassette of substrates (not shown) is loaded in a load-lock chamber **103a,b**, the robot **107** may select a first substrate **102** and transfer the selected substrate to the measurement chamber **105**. The dimensions of features **85** or the attributes of different regions **144, 146** of the substrate **102** are measured in the measurement chamber **105** using for example, a process monitor **180** such as a metrology tool **400**. Signals corresponding to these measurements are passed to the chamber controller **300**, which then selects a process recipe from a look-up table that has suitable process parameters to process the batch of substrates **102** in the cassette which have the same measured attributes. For example, if the measured dimension of the features **85** were bigger than average, the process recipe would have process conditions that remedy the problem by excessive etching of the features **85**, or vice versa. These measurements can also be made between process steps on a single substrate, by removing the substrate **102** from a process chamber **104** and passing it to the measurement chamber **105** for measurements, and then returning it to the process chamber **104** for further processing in processing conditions according to a process recipe selected based on the measurement signals.

In another embodiment, the chamber controller **300** changes the process parameters in the chamber **104** from initializing process parameters used in the processing of an initial substrate, to batch process parameters for the processing of a batch of substrates similar in attributes to the initial substrate. In this version, an initial or first substrate is taken from a batch of substrates in the substrate cassette and transferred to the chamber **104** for processing. Before and after processing, or during processing, the dimensions of features **85** in more than one region of the substrate **102** are measured and the resultant dimension measurements correlated to the dimensions measured at the different regions after processing of the substrate is completed. The original difference in dimensions of the features **85** in different substrate regions and/or the change in dimensions of the features **85** at the different regions after processing is evaluated by the chamber controller to determine a particular set of batch process parameters or a process recipe from a look-up table to reduce the difference in dimensions at the conclusion of processing for subsequent substrates. The other substrates of the batch, which are similar in attributes to the initial substrate, are then processed to the determined process recipe or batch process parameters to further reduce variations in critical dimensions of the features **85** at the different regions across the subsequent substrates in the batch. This method allows compensation for process variations or anomalies from one batch of substrates to another batch.

Process Monitor

Different versions of the process monitor will be detailed. In one version, the process monitor **180** comprises a plurality of interferometers **181a,b** that detect light, such as visible or ultra-violet light, that is reflected from features **85** being etched at the different regions **144, 146** of the substrate **102** to determine a state of the features **85** at each region at a given time, as shown in Figure 1b. For example, a first interferometer **181a** has a first light source **184a** that directs a first light beam **186a** toward a first central region of the substrate to generate a reflected light beam **186b** that is received by the first detector **182a**, which then generates a first signal in relation to the intensity of reflected light beam. A second interferometer **181b** comprises a second light source **184b** directs a second light beam **188a** toward a second peripheral region **146** from which it is reflected to form the beam **188b** that is received by a second detector **182b**, which then generates a second signal. Each light source **184a,b** can be

a monochromatic light source, such as for example, a He-Ne or ND-YAG laser; or a polychromatic light source, such as a xenon or Hg-Cd lamp. The polychromatic light source may be filtered to provide a light beam having the selected wavelengths or a light filter can be placed in front of the detector. The interferometers **181a,b** can also use light generated by the plasma in the chamber as the light source. The light detectors **182a,b** typically comprise a light sensitive sensor, such as a photomultiplier, photovoltaic cell, photodiode, or phototransistor, that provides an electrical intensity signal in response to a measured intensity or phase of the reflected light beams **186b, 188b** from the substrate **102**. Focusing lenses **190a,b** can be used to focus the light beams **186, 188** onto different spots on the substrate **102** or to focus reflected light back onto the light detectors **182a,b**. Optionally, light beam positioners **192a,b**, such as rotable mirrors, can be used to locate a suitable location on which to "park" the beam, direct reflected light onto the light detectors **182a,b**, or scan the light beams **186a, 186b** in a raster pattern across the substrate **102**.

When the area of the features **85** being formed in the substrate **102** is relatively small compared to the surrounding areas that are not being processed, it is desirable to increase the signal to noise ratio of the measurements of the dimensions of the features **85**. In one version, one or more light polarizers **196a,b** are used to polarize the light before or after it is reflected from the substrate **102** to increase a signal to noise ratio of the reflected light signal from the substrate features **85**, as for example disclosed in U.S. Patent Application No. 09/695,577, by Sui et al., entitled "Monitoring Substrate Processing Using Reflected Radiation," which is incorporated herein by reference in its entirety. The polarization angle relates to a principal orientation of the features **85**, which is a primary direction of a majority of the features **85** being processed on the substrate **102,** and can include a first polarization angle substantially parallel to the principal orientation and a second polarization angle substantially perpendicular to the principal orientation. The intensity of reflected light component having the substantially parallel polarization angle has a larger magnitude than reflected light components that are at other polarization angles. Thus measured parallel and other reflected light components are used to enhance the signal strength of the light reflected from the features **85** of interest relative to light reflected from other portions, such as from the resist portions or adjacent regions of the substrate **102**, to increase the signal to noise ratio of the reflected light. The depth of a feature **85** being etched on

the substrate **102** or the etch rate can be determined by monitoring the reflected polarized light. Thus, the etch depth of a feature **85** being formed on a substrate **102** may be determined by counting the minima or maxima of the signal resulting from the destructive/constructive interference of the reflected polarized light.

The interferometers **181a,b** can also have filters **194a,b**, such as bandpass filters, to selectively filter the signals generated by the light detectors **182a,b** to increase the relative intensity of a selected passband of frequencies or wavelengths of the signals in relation to the intensity of other frequency components of the reflected light. The passband can be related to an intensity modulation frequency of the reflected light from the features **85** being formed on the substrate **102** to reduce the intensity of any light signal that is not reflected from other portions of the substrate **102**. The bandpass filter can be an optical signal processor, such as a coated lens or material, or an electrical signal processor such as a digital signal processor that digitizes a light signal received from the light detectors **182a,b** and filters the digitized signal. In one version, the passband range is selected to provide a coherence length of a non-coherent light source, which may be, for example, a plasma emission having multiple wavelengths and phases. The coherence length is the length in which interference effects of light from the light source can be observed. In one version, the passband range of the bandpass filter can be 1.5 nanometers for a plasma emission centered at about 254 nanometers.

In another version, the process monitor **180** comprises a plasma emission analyzer to measure a quantitative value of the feature dimensions from the changing emission spectra of the feature processing plasma. The plasma emission analyzer comprises a first detector **182a** that detects light emitted from the plasma in the first zone **136** above a first portion **144** of the substrate **102**, and a second detector **182b** to detect light emitted from the plasma in the second processing sector **138** above a second portion **146** of the substrate **102**, as shown in Figure 1c. Each light emission from a predefined plasma location is used to generate a separate signal, which may be outputted as different signals or as a combined signal. The plasma emission analyzer analyzes the emission spectra of different plasma regions to determine a change in the chemical composition or other attribute of the features **85** being formed at this region. The emissions spectra can change, for example, with etch through one layer and

commencement of etching into another layer having a different chemical composition. Optionally, focusing lenses **190a,b** can be used to focus the detectors **182a,b** onto different spots in the plasma over the substrate **102** and light beam positioners **192a,b** can be used to move the detection position of the detectors **182a,b** or the direction of sight of the lenses **190a,b**.

In yet another version, the process monitor **180** comprises a reflectometer (not shown) which directs a light beam onto the substrate **102** and detects the amplitude of the reflected beam, as for example disclosed in U.S. Patents No. 6,462,817 and 6,297,880 which are incorporated herein by reference in their entirety. A reflectometer can be used to determine properties such as the thickness or index of refraction of features **85** being formed on the substrate **102**. The reflectometer comprises a laser or other light source to direct a beam of light onto a portion of the substrate **102** and a light detector to measure the intensity of the reflected beam. The reflectometer may also comprise an adjustable filter to control the wavelength of the incident or reflected beam. Alternatively, the reflectometer may measure a band of wavelengths simultaneously. The reflectometer can also comprise a means to adjust the angle of incidence of the beam directed onto the substrate **102**. In another version, the reflectometer may use a polarized incident light beam, and to this end may further comprise a polarizer and a phase retarder or modulator, as previously described. For example, when the reflectometer is used to determine the thickness of features **85** having a known wavelength-dependent index of refraction and an extinction coefficient of zero, the reflectometer uses unpolarized light at normal incidence and measures the ratio of the intensity of the reflected beam to the incident beam as a function of wavelength. From a plot of reflection intensity vs wavelength, and the known index of refraction, a thickness of the features **85** can be calculated using Maxwell's Equations. For example, in reflection from a single layer of features **85**, the expected reflection intensity primarily depends on the index of refraction of the feature material (which is wavelength and angle dependent), and the thickness of the feature **85**. Since the wavelength dependence of the index of refraction is known, and the angle of incidence is not varied, the collected data can be used to solve for the thickness of the features **85**. In another version, the angle of incidence can be varied, as well as the polarization of the incident beam, to generate data that can be collected, for example the reflection intensity can

now be measured as a function of angle and polarization, as well as of wavelength, and solved for complex layered features **85**.

In yet another version, the process monitor **180** comprises an ellipsometer (not shown), which directs a polarized light beam onto the substrate **102** and detects both the change in the phase and magnitude of the reflected light beams from the substrate **102**. The light beam is polarized into components parallel (p component) and perpendicular (s component) to the plane of incidence onto the substrate. The amplitude and phase of the ratio of the reflected s and p components are referred to as the ellipsometric parameters ψ and Δ by mathematical equations that are known in the art. Examples of ellipsometers are disclosed in U.S. Patent Numbers 3,874,797 and 3,824,017, both of which are incorporated herein by reference in their entireties.

In a further version, the process monitor **180** is a metrology tool **400** that monitors dimensions of features **85** being processed on a substrate in-situ in the process chamber **104** or in a measurement chamber **105** outside the process chamber **104** in a processing line of the substrate processing apparatus **100**. The substrate **102** can be transferred from the process chamber **104** to the measurement chamber **105** where the substrate **102** is measured by the metrology tool **400**. The metrology tool **400** can also be mounted in a separate chamber, such as the load-lock chamber **103a,b** or the transfer chamber. The resulting metrology data from the substrate **102** is used to adjust the process parameters to improve processing of other substrates as described below. The metrology tool **400** measures a property of the substrate **102**, such as a critical dimension (CD), line profile, or other shape characteristic of features **85** in the substrate **102**, before or after processing of the substrate **102.** An embodiment of a metrology tool **400**, as illustrated in Figure 11, comprises an optical measurement device capable of measuring topographical dimensions of the processed features **85**, such as feature width, height, spacing, shape, or taper angle of the edge of the feature **85**. For example, in one version, the metrology tool **400** is a diffractive line profilometer that directs a polarized, broadband light beam onto the substrate **102** and measures the resulting reflectively diffracted light beam to determine an average line profile of the features **85** in a targeted region **144, 146** of the substrate **102**. The features **85** form a diffraction grating on the substrate **102**. Typically, the features **85** are periodic within the region, such as an array of lines. The metrology tool **400**

comprises a model of the periodic features **85** with tunable parameters that determine the shapes of the features **85**. An initial profile estimate of the features **85** is entered into the metrology tool **400**. The metrology tool **400** calculates the diffraction spectrum from this initial profile estimate, such as using Rigorous Coupled Wave Analysis (RCWA). A mismatch between the calculated diffraction spectrum and the detected diffraction spectrum is used to optimize the profile estimate using a non-linear regression algorithm. This optimization step is repeated until the calculated diffraction spectrum of the profile estimate is within a desired tolerance of the detected diffraction spectrum. Exemplary embodiments of a suitable metrology tool **400** that include a diffractive line profilometer are the NanoOCD models, fabricated by Nanometrics, Milpitas, California. An example of a method of diffractively determining a line profile of repeating features **85** in an area is further described in U.S. Patent No. 5,963,329 to Conrad et al., which is hereby incorporated by reference in its entirety.

In another exemplary embodiment, the process monitor **180** can also be a scatterometer (not shown) capable of 2-Θ scatterometry, in which the intensity of the scattered light is measured as a function of the angle of incidence. Light is diffracted by periodic features **85** on the substrate **102** according to the grating equation: $\sin\theta_i + \sin\theta_r = m\lambda/d$, where θ_i is the angle of incidence, θ_r is the angle of reflection, m is the diffraction order, λ is the wavelength of light, and d is the period of the pattern being evaluated on the substrate **102**. For small values of the grating period, corresponding to small feature sizes, usually m=0, corresponding to angle of incidence equals angle of reflection, is the diffraction order most easily observed. In scatterometry, the incident or reflected light can also be polarized into s and p components to provide better measurements. Analysis of the data to determine properties of the substrate **102** being processed may involve either solving mathematical models based on collected data or the comparison of collected data to previously computed solutions to determine a best fit, for example by using algorithims that minimize the root mean square error (RMSE) between the observations and the solutions.

In the version shown in Figure 11, the metrology tool **400** comprises a light source **410** to produce an incident light beam **415**. A partially reflective mirror **420** diverts the incident light beam **415** toward the substrate **102** to illuminate the substrate **102** and generate a reflected light beam **425** that is reflected from the substrate **102**.

The reflected light beam **425** passes through the partially reflective mirror **420** and into a light detector **430** comprising a light-sensitive device. Optical elements **435a-c** can be provided between the light source **410**, partially reflective mirror **420**, substrate **102**, and light detector **430** to focus, aperture, stigmate, or otherwise modify the incident and reflected light beams **415, 425**. For example, the optical elements **435a-c** may comprise lenses and adjustable apertures. A metrology control system **440** may be provided to control the optical elements **435a-c** and the substrate support **114** to make measurements of the substrate **102** with a desirably high precision. In one embodiment, the light detector **430** is adapted to measure multiple amplitudes across the frequency spectrum of the reflected light beam **425** to measure a critical dimension (CD) of a target feature of the substrate **102**. For example, the light detector **430** may comprise a single light-sensitive electronic device such as an array of light-sensitive photoelectric sensor, for example a CCD detector. An image processor **445** receives the image from the light detector **430** and processes the image to determine the critical dimensions of features **85** on the substrate **102**. Typically, image boundaries corresponding to topological features of the substrate **102** are digitally outlined by differentiating between ranges of intensity levels in the electronic image. The critical dimension of a target feature is calculated by measuring the distance between image boundaries corresponding to the edges of the target feature.

In another exemplary embodiment, the light detector **430** is adapted to determine a thickness of features **85** of the substrate **102** by spectroscopic ellipsometry. Upon entering the light detector **430**, the reflected light beam **425** has a polarization angle that is detected to calculate the change in thickness of the features **85**. For example, the polarization angle of the reflected light beam **425** can be determined for the substrate **102** when features **85** have a first thickness. Subsequently, the polarization angle of the reflected light beam **425** can be determined for the substrate **102** when the features **85** have a second thickness. The difference between the first and second thickness is calculated by dividing the change in polarization angle by a predetermined rate of change of the polarization angle along the propagation distance of the reflected light beam **425**.

Controller

Referring to Figure 2a, typically, the chamber controller **300** comprises as a computer **308** having a central processing unit (CPU) **312**, such as a Pentium processor commercially available from Intel Corporation, Santa Clara, California, coupled to a memory **316** and peripheral computer components. The memory **316** may include a removable storage **320**, such as a CD or floppy drive; a non-removable storage **324**, such as a hard drive; and random access memory (RAM) **328**. The chamber controller **300** may further comprise a hardware interface **304** comprising analog or digital input and output boards, and motor controller boards. An operator can communicate with the chamber controller **300** via a display **332** or data input device **336**. To select a particular screen or function, the operator enters the selection using the data input device **336**, such as a keyboard or light pen.

The chamber controller **300** also comprises a computer-readable program **348** stored in the memory **316**, and comprising program code capable of controlling and monitoring the processes conducted in the chamber **104**. The computer-readable program **348** may be written in any conventional computer-readable programming language. Suitable program code is entered into single or multiple files using a conventional text editor and stored or embodied in computer-usable medium of the memory **316**. If the entered code text is in a high level language, the code is compiled, and the resultant compiler code is then linked with an object code of pre-compiled library routines. To execute the linked, compiled object code, the user invokes the object code, causing the CPU **312** to read and execute the code to perform the tasks identified in the program **348**. An illustrative control structure of an embodiment of a computer-readable program **348** is shown in Figure 2b.

Using the data input device **336**, for example, a user enters a process parameter set and chamber number **104a,b** into the computer-readable program **348** in response to menus or screens displayed on the display **332** that are generated by the process selector instruction set **352**. A process sequencer instruction set **356** comprises program code to accept a chamber type and set of process parameters from the process selector **352** and time its operation. The process sequencer instruction set **356** initiates execution of the process set by passing the particular process parameters

to a chamber manager instruction set **360** that controls multiple processing tasks in the chambers **104a,b**. For example, the chamber manager instruction set **360** can include various chamber component instruction sets, such as:

(1) a substrate positioning instruction set **364** to control chamber components to load the substrate **102** onto the substrate support **114**, and optionally, to lift the substrate **102** to a desired height in the chambers **104a,b**;

(2) a gas flow control instruction set **368** to control the composition, flow rates through different gas outlets **140, 142**, and velocities of the etching gas introduced into the chambers **104a,b**;

(3) a gas pressure control instruction set **372** to control the pressure in the chamber **104** by regulating the opening size of the throttle valve **163**;

(4) a temperature control instruction set **376** to control the temperatures at different regions **144, 146** of the substrate **102**, by for example, operating a heater (not shown) in the support **114**, flow rates of heat transfer gas, or radiant energy lamps (also not shown);

(5) a gas energizer control instruction set **380** to control the power level applied to a gas energizer **165** of the chambers **104a,b**; and

(6) a magnetic field control instruction set **392** to operate an optional magnetic field generator **170**; and

(7) a process monitoring instruction set **384** to monitor a process being conducted in the chamber **104**; and

(8) a process feedback control instruction set **388** to serve as a feedback control loop between the process monitoring instruction set **384** and other chamber component instruction sets.

While described as separate instruction sets for performing a set of tasks, each of these instruction sets can be integrated with one another or may be over-lapping; thus, the chamber controller **300** and the computer-readable program **348** described herein should not be limited to the specific version of the functional routines described herein.

The process monitoring instruction set **384** comprises, for example, (i) a first detector instruction set **385** to receive and/or evaluate a first signal generated by

the first detector **182a** from the light beam **186a** reflected from the first region **144** of the substrate **102**, and (ii) a second detector instruction set **386** to receive and/or evaluate a second signal generated by the second detector **182** from the light beam **188b** reflected from a second region **146** of the substrate **102**, to determine comparative information about the processing state at the different regions **144, 146**. Each signal is evaluated to determine an attribute of the features **85** being processed in the substrate region from which the signal is generated. For example, when the process monitor **180** comprises interferometers **181a,b**, the process monitoring instruction set **384** can count the number of interference fringes in each of the two signals; or compare the intensity of the signals in real-time to a stored characteristic waveforms, measured or calculated representative data patterns, or data stored in a look-up table. The process monitoring instruction set **384** can also comprise program code for controlling the light sources **184a,b**; bandpass filters **194a,b**, light beam positioners **192a,b**, focusing lenses **190a,b,** or light polarizers **196a,b**.

The detection parameters instruction set **387** comprises code relating to the detection parameters, such as selected wavelengths; characteristic attributes of reflected or emissive light; timing data; predetermined numbers of interference fringes; the look-up table; algorithms for modeling the data; and other data types and patterns. The data parameters can be determined by processing test substrates having predetermined feature dimensions, one at a time, in the chambers **104a,b**. For example, a series of traces of light reflected from features **85** having different dimensions on the substrate **102** and/or emitted from different regions of the plasma in the chamber **104** are recorded. The traces are evaluated to identify a recognizable detectable change in the trace, which is used as input and programmed into the detection parameters instruction set **387**, in the form of an algorithm, look-up table, stored parameters, or other criteria suitable for evaluating the dimension of the features **85** being processed on the substrate **102**.

The process feedback control instruction set **388** forms a feedback control loop between the process monitoring instruction set **384** and other chamber component instruction sets. The process feedback instruction set **388**, in response to signals from the process monitoring instruction set **384**, generates and sends signals to instruct the chamber component instruction sets to set process parameters at different localized

levels at different regions of the substrate **102**. For example, the process feedback instruction set **388** can retrieve the look-up table from the memory **316** of the chamber controller **300** and identify a suitable recipe or sets of localized process parameter values for the chambers **104a,b** from the look-up table that is associated with the values of the process monitoring signals received from the process monitoring instruction set **384**. In another example, the chamber controller **300** can mathematically compute one or more localized process parameter levels from the first and second signal levels received from the process monitor **180**.

Controlling Gas Flow to Regulate Feature Dimensions

In this example, the first and second signals of the dimensions of the features **85** being processed in the first and second regions **144, 146** of the substrate **102** and to control the gas flow rates of a process gas that is directed into the first and second processing sectors **136, 138**. By setting two different localized gas flow rates, the chamber controller adjusts for any detected difference in feature dimensions at the different substrate regions **144, 146** to compensate for the dimensional differences.

In one version, the gas distributor **122** is connected to gas supplies **124a-c** via conduits **126a-c** having gas flow control valves **128a-c** that are controlled to pass a desired gas composition to a mixing manifold **130**, as shown in Figure 1b. The mixing manifold **130** mixes the gases to form a process gas that is fed to a flow splitter **132** that divides the flow of gas between the different gas outlets **140,142** of a gas nozzle **134**. The gas outlets **140,142** introduce the process gas at different flow rates ino the processing sectors **136,138** of the process zone **112** of the chamber **104** so that different gas flow rates are provided directly above different portions **144, 146** of the substrate **102**. However, the gas outlets **140, 142** can also be positioned to direct the gas into other regions of the chamber **104** or substrate **102**. The gas outlets **140, 142** can extend through the ceiling **106** (as shown), sidewall **108** or support **114** (not shown).

The gas distributor **134** also has a flow splitter **132** having a single input channel that receives premixed etching gas and a bifurcated valve leading to two output channels to generate two output gas streams of the same process gas for the central and peripheral gas outlets **140, 142**. The bifurcated valve can simultaneously set both

the first and second flow rates to first and second output channels. The single input channel provides more controllable ratio of flow rates through each output channel since the setting one flow rate automatically sets the other to the desired level without requiring calibration of two separate gas flow valves to one another. However, the flow splitter **132** can also have individual gas flow valves on separate conduits that lead from the mixing manifold **130** to the central and peripheral gas outlets **140, 142,** respectively. The latter version allows individual control of each of the valves which is desirable when, for example, one of the flow rates need to be individually adjusted without changing the other flow rate.

The gas distributor **134** also has multiple gas outlets **140**, **142** that are spaced apart and positioned to generate a non-uniform distribution of process gas into the chamber **104** to improve processing uniformity across the substrate **102**. The arrangement of the gas outlets **140**, **142** can be determined from gas flow modeling using computation fluid dynamics, or by experimental studies with test substrates. For example, central and peripheral gas outlets **140, 142** can be located to provide gas flow ingress points that generate concurrent but separate flow patterns of gas to different processing sectors **136**, **138** to control the localized gas species distribution or gas residence time about the different regions **144, 146** of the substrate **102**. The peripheral gas outlets **142** are spaced apart along a ring that is radially outward from, and coaxial to, the central gas outlets **140**, which are spaced apart along an inner circle, as shown in Figure 1e. A window **113a** is in the circle inside of the central gas outlets **140** to allow light to pass through for the process monitor **180**. The gas outlets **140, 142** can also be positioned along the same radial line or can be positioned on alternating radial lines. In one version, the gas distributor **122** has 12 central gas outlets **140** and 12 surrounding peripheral gas outlets **142**.

The gas outlets **140, 142** can also have different opening sizes selected to inject gas with different velocities. For example, the central gas outlets **140** can have an opening size set to provide a first gas velocity, and the peripheral gas outlets **142** another opening size to provide a second velocity of gas. In one embodiment, the opening sizes are selected to provide a first velocity that is at least about 1 time higher than the second velocity. The different velocities result in different residence times of each gas flow stream that generate a flow distribution in the chamber **104** that equalizes other non-controllable processing variables. For example, the higher gas velocity region

can provide different etching attributes by replenishing the process gas species at a faster rate and thereby improving, for example, chemical reaction or isotropic etching attributes in the region, which would control the shape of the features **85** being processed at the region.

The gas outlets **140, 142** can also be adapted to direct gas along flow directions **148, 150** that are at different angles relative to one another. For example, the gas outlets **140** can be oriented to direct gas in a vertical direction **148** that is substantially perpendicular to the receiving surface **116** of the substrate support **114,** as shown in Figure 1c; or the gas outlets **142** can be oriented to direct gas at an angled flow direction **150** that is inclined to the receiving surface **116**, as shown in Figure 1b. The vertically oriented first flow direction of process gas provides a perpendicular gas stream on the central region **144** of the substrate **102** and the angled second flow direction provides an inclined gas stream over the peripheral region **146** of the substrate **102**. The gas outlets **140, 142** can also direct the gas flow streams horizontal and parallel to the receiving surface **116** of the substrate support **114** (not shown). The difference in directed angles of the two gas streams can also control the flow rate and incidence angle of fresh process gas at each of the different regions **146, 148** of the substrate **102.**

In this version, the process feedback control instruction set **388** of the chamber controller **300** transmits instructions to the gas flow control instruction set **368** to control the gas flow rates through the gas outlets **140, 142** in response to the first and second monitoring signals. The gas flow control instruction set **368** also comprises, for example, a control valve instruction set **369** that includes program code to set the positions of the gas flow control valves **128a-c** of the different gas supplies **124a-c** to obtain a particular process gas composition. The gas flow control instruction set **368** can also comprises a flow splitter instruction set **370** that has program code to adjust the flow splitter **132** to pass a first volumetric flow rate of process gas through the central gas outlets **140, 142** and a second volumetric flow rate of process gas through the peripheral gas outlets **140, 142** to obtain the desired volumetric flow ratio through one or both of the gas outlets **140, 142**. For example, if a critical dimension of features **85** being etched on the substrate are reached at a faster rate at a first central region **144** of the substrate **102**, relative to a second peripheral region **146**, the process

feedback control instruction set **388** instructs the gas flow control instruction set **368** to operate the flow splitter **132** to reduce a flow rate of etching gas passing through the central gas outlets **140** and increase a flow rate of etching gas passing through the peripheral gas outlets **142**. In this manner, a process parameter comprising localized gas flow rates is controlled at the different processing sectors **136, 138** to control the attributes of the features **85** being etched at the different regions **144, 146** of the substrate **102**. Similarly, the gas flow control instruction set **368** can operate the flow rates or an opening size of the gas outlets **140, 142** themselves, to control the velocity of gas passing through the outlets. The localized gas flow rates or velocities can also be set to match the attributes of features **85** being etched at the central and peripheral regions **144**, **146** of the substrate **102** to obtain dimensions that are substantially identical, i.e., that vary by less than 5 %, at both regions **144, 146**.

In another example, the process feedback control instruction set **388** mathematically computes the localized process parameter levels from the first and second signal levels received from the process monitor **180**. For example, for a first signal level of S_1, and a second signal level S_2, the value of a difference in first and second process gas flow rates ΔF, can be calculated from the formula: $\Delta F = k(C_1 S_1 - C_2 S_2)$, where C_1, C_2, and k are experimentally determined constants to a particular process recipe and equation. The chamber controller **300** then uses ΔF to instruct the flow splitter instruction set **370** to set the opening position of the flow splitter so that a desired flow rates of process gas pass through each set of gas outlets **140, 142**. The first and second flow rates may be set in relation to the first and second signals, so that the first flow rate is proportional in magnitude to the first signal level and the second flow rate is also proportional in magnitude to the second signal level. For example, when the features **85** being etched in the first region **144** of the substrate **102** are being etched too slowly relative to the features **85** at the second region **146** of the substrate **102**, causing their critical dimensions to become different, the first flow rate is set at a higher level than the second flow rate to provide more etching gas at the first region **144** of the substrate **102** to reduce the variation in the etch rates and critical dimensions.

Examples

The following examples demonstrate process control of the etching dimensions of features **85** being etched at the different regions **144, 146** of the substrate **102** in a DPS-type chamber as partially illustrated in Figures 1c and 1e. A process monitor **180** comprising an interferometer was used to detect light that was reflected from the substrate **102** and passed through the window **113a** located at the center of the ceiling **106**. Etching gas was introduced into the chamber **104** either through (i) only the peripheral gas outlets **142**, (ii) only the central gas outlets **140**, or (iii) through both the central and peripheral gas outlets **140, 142** in different flow ratios. The central gas outlets **140** directed gas vertically into the chamber **104** at an angle of 0° relative to the normal to the plane of the substrate **102**, and the peripheral gas outlets **142** directed etching gas at either an inclined angle of 45° or at an angle of 90° relative to the normal to the plane of the substrate **102**. During the etching process, the chamber controller **300** sets the etching gas composition and flow rates through each of the different gas outlets **140, 142**, in relation to signals received from the detectors of the process monitor.

The features **85** were etched in a blanket polysilicon layer on a silicon wafer using an etching gas comprising HBr and HeO_2 and optionally Cl_2; or Cl_2, O_2, and N_2. The main etch step was performed at a gas pressure of about 4 mTorr, and an etch finishing (soft landing) step was conducted at a higher pressure of about 30 mTorr. The antenna source power level was typically maintained at 200 to 800 Watts and the electrode bias power level at 40 to 400 Watts. After etching, the attributes of the etched features **85** was determined or confirmed using a scanning electron microscope (SEM).

Figure 3 demonstrates that controlling the gas flow rates through the central and peripheral gas outlets **140, 142** provides more uniform etch rates for features **85** at different regions 144, 146 across the substrate diameter. The Y-axis shows the measured relative etch rate of features **85** etched along a line drawn across the substrate diameter from the center to opposing perimeters of the substrate **102**. The X-axis represents distance from center across the diameter of a 300mm substrate, where the 0 mm point represents the center of the substrate **102**, the (-150 mm) point represents a first perimeter point, and the (150 mm) point represents the opposing

perimeter. When etching gas was introduced through the peripheral gas outlets **142**, the etch rate of the features **85** located at about the central region **144** of the substrate **102** was much slower and dipped downwards relative to the etch rate of the features **85** about the two opposing peripheral regions **146** of the substrate **102**. Conversely, when the etching gas was introduced only through the central gas outlets **140**, the etch rate of the features **85** at the central region **144** were higher than the etch rates at the peripheral region **146**. When the gas flow was controllably applied through both the central and peripheral gas outlets **140, 142**, the etch rate of features **85** at the central and peripheral regions **144, 146** of the substrate **102** had much less variance ranging from about 1150 to about 1275 A/min. This prospective example demonstrates that a closed control loop setting different gas flows with the gas distributor **134** having a combination of central and peripheral gas outlets **140, 142** can reduce etch rate variance and significantly improve etch rate uniformity across the substrate **102**.

Figure 4 shows results in which the flow splitter **132** of a gas distributor **134** was set to provide gas flow from either only from (i) the peripheral outlets **142** or the (ii) central gas outlets **140**, or both outlets **140, 142** either (iii) fully open (1:1) or (iv) both outlets **140, 142** open 50% (0.5:0.5). The central only gas flow pattern provided relatively higher etch rates of up to about 6200 angstroms/minute at the central region **144** and lower etch rates of about 5800 at the peripheral region **146** of the substrate **102**, and a peripheral gas flow provided lower etch rates between about 4500 and 5000 angstroms/minute at the central region **144** and higher etch rates of about 6000 angstroms/minute at the peripheral region **146** of the substrate **102**. Maintaining both the central and peripheral gas outlets **140,142** open provided etch rates that varied between 5200 and 6000 angstroms/minute. The etch ratio is a measure of a dimension such as thickness or depth of a feature **85**.

Figure 5 demonstrates the predicted variation in another dimension, the taper angle of etched features **85**, across a radial section from the peripheral region **146** to the central region **144** of the substrate **102** for increasing flow ratios of etching gas passed through the peripheral gas outlets **142** relative to the central gas outlets **140**, where 0 indicates only central gas outlet flow and 1 indicates only peripheral gas flow. The taper angle of the etched features **85** was simulated across a radial section of features **85** having a line width of 0.18 microns, and that were relatively isolated from

one another. These figures demonstrate that the taper angle of the etched features **85** is also significantly influenced by controlling the gas flow distribution by passing different flow ratios of etching gas through the central and peripheral gas outlets **140, 142**. When the etching gas was passed only through the central gas outlets **140**, the taper angle of the etched features **85** at the central region **144** of the substrate **102** exceeded 84° while the taper angle at the peripheral region **146** of the substrate **102** was closer to a desirable 82° angle. In contrast, when all the etching gas was passed through the peripheral gas outlets **142**, the taper angles ranged on the lower side from 77 to less than 80°, and were higher at the peripheral region **146** than the central region **144**. Good taper angle uniformities were obtained at peripheral to center gas flow ratio settings of from about 2:1 to about 4:1 and more preferably about 3:1. A similar pattern was predicted for the etching of features **85** in a feature-dense region of the substrate **102** (not shown).

Figure 6 shows the predicted taper angle uniformity as a ratio of peripheral to central gas outlet flow rates and for etching of isolated and dense feature regions on the substrate **102**, according to a taper etch simulation model. The optimal range of taper angles of about 1, which indicates the best taper angle uniformity, is the same for both the isolated and dense feature regions and is at a flow ratio of about 75 percent which corresponds to a 3:1 (75%) flow rate ratio of etching gas passed through the peripheral and central gas outlets **142, 140**, respectively. At the 3:1 ratio, the lowest variability range of taper angles of the etched features **85** were obtained across the substrate **102**.

Figure 7 shows a comparison of the measured taper angles of the etched features **85** located at different points across the radius of the substrate **102** for a new and baseline process. In this example, the gas distributor **122** in the chamber **104** comprises first, or central, gas outlets **140** oriented to direct etching gas has an angle of about 10° relative to the normal to the plane of the substrate **102**, and second, or peripheral, gas outlets **142** oriented to direct the etching gas at an angle of 30° relative to the normal to the plane of the substrate **102**. The gas outlets **140, 142** were drilled into a 10 inch diameter gas distributor **134** made from quartz. The taper angles for a 3:1 flow ratio process were found to increase to the range of 84 to 86° instead of the 82 to 84° range provided by a baseline process. The increase in average taper angle

represented a 1 to 5° increase in taper angle over the baseline process. The range of taper angles is also narrower at about 2 to 2.5°, especially when considering the increased taper angle values, which should exhibit a higher variation rather than a lower one. The average depth of the etched features **85** also increased from about 2800 to about 2900 angstroms, while reducing the 1σ statistical deviation to from 44 to 69. These results represented a significant improvement over baseline processes that provided lower average taper angles and higher ranges of variations in taper angles for features **85** at different regions **144, 146** across the substrate **102**.

Controlling Magnetic Field Strengths to Regulate Feature Dimensions

The process monitoring signals from different regions **144, 146** of the substrate **102** can also be used to control the processing of features **85** at the different regions by setting different levels of, or multivariate intensity levels, of a magnetic field strength across the different processing sectors **136,138** of the process zone **112**. When the magnetic field generator **170** is present, the chamber controller **300** comprises a magnetic field control instruction set **392** to control the magnetic field strengths at localized processing sectors **136, 138** in the chamber **104**. For example, the magnetic field control instruction set **392** can provide instructions to the magnetic field generator **170** to generate a magnetic field having different controllable first and second field strengths in each processing sectors **136, 138** so that the first and second regions **144, 146** of the substrate **102** are each exposed to a different magnetic field strength. The process feedback control instruction set **388** evaluates the signals from the process monitor instruction set **384** and sends instructions to the magnetic field control instruction set **392** to operate the magnetic field generator **170** to set different magnetic field strengths in relation to the evaluated signals. The variable magnetic field may be used to control plasma sheath density above different regions **144, 146** of the substrate **102**, stir up the plasma ions by applying a rotating or changing magnetic field, or contain the plasma and reduce spreading of plasma into the exhaust port **158**. Each magnetic field strength can be independently controllable so that each may be adjusted to have a particular strength value at a particular region **144, 146** of the substrate **102**. However, if the difference between the two magnetic field strengths is constant for a particular process, then the magnetic field generator **170** can use a process recipe that sets a magnetic field to two fixed field strengths at two different positions in the chamber

104, for example, a first fixed field strength above the central region **144** of the substrate **102** and a second fixed field strength above the peripheral region **146** of the substrate **102**.

The different magnetic field strengths control the passage or motion of the plasma species at different regions **144, 146** of the substrate **102** to control processing characteristics at these different regions. For example, to match the attributes of features **85** being etched at the central and peripheral regions **144, 146** of the substrate **102**, a first magnetic field strength can be applied about a second radially peripheral region **146** of the substrate **102** that is higher than a second field strength about a first central region **144** of the substrate **102**, by for example, at least about 20%, or even at least about 40%. The magnetic field strength at the different regions **144, 146** can also be set to provide increased stirring of the plasma ions at outer region **146** relative to the inner region **144**, or vice versa, by adjusting the frequency of the current applied to magnetic field generator **170**.

An exemplary version of a magnetic field generator **170** on a chamber **104a,** such as for example, an MxP+ or eMax type chamber from Applied Materials, Inc., Santa Clara, California, is shown in Figures 1f and 1g. The magnetic field generator **170** generates a controllable magnetic field in the processing sector **112** of the chamber **104a**. The magnetic field generator **170** can comprise permanent magnets or electromagnets, as for example described in U.S. Patent No 4,842,683, issued June 27, 1989, which is incorporated herein by reference in its entirety. In one embodiment, illustrated in Figure 1f, the magnetic field generator **170** comprises an assembly of concentric pairs of electromagnets **202a-h** that control the radial spatial density distribution of the plasma while generating a rotating magnetic field that is parallel to the plane of the substrate **102**. The rotating magnetic field has an angular orientation and magnitude that varies over time and is the vector sum of the magnetic fields produced by each electromagnet **202a-h**. One pair of electromagnets **200a,b** comprises two electromagnets **200a,b** that are concentric and co-planar to generate a magnetic field with independent central and peripheral field strengths. The concentric electromagnets **202a-h** are positioned adjacent to the chamber **104a** and are powered by an electromagnet power source **204** comprising independent power supplies **202a-h** that are adjusted by the chamber controller **300** to independently control the currents

applied to the electromagnets **200a-h** to independently control the central and peripheral field strengths. The electromagnet power source **204** also energizes the electromagnet pairs in a sequence to generate a rotating, multi-directional magnetic field.

The electromagnets **200a-h** are arranged to generate first and second magnetic field strength vectors $\mathbf{B_p}$, $\mathbf{B_c}$ in different etching zones **136, 138** in the chamber **104a**. Each magnetic field strength vector $\mathbf{B_p}$, $\mathbf{B_c}$ has mutually perpendicular magnetic vectors B_x and B_y, respectively, which are generally parallel to the substrate receiving surface **116**, as disclosed in commonly held U.S. Patent No. 5,215,619, which is incorporated herein by reference in its entirety. The magnetic power source **204** has a number of conventional electromagnet power systems **202a-h** to control the magnitudes and directions of the currents supplied to the electromagnets **200a-h** according to instructions provided by the chamber controller **300**. The associated currents determine the orientation and magnitude of the magnetic field generated by each coil pair. Alternatively, the chamber controller **300** can control oscillatory movement of a set of permanent magnets of ferromagnetic material positioned in an armature that can be rotated in a circular/elliptical form or oscillated in a linear direction. The perpendicular field vectors B_y and B_x generated by the electromagnetic field generator **170** are defined by the functions $B_x=B\cos\theta$; and $B_y=B\sin\theta$. Given the desired set of values of the field, B, and its angular orientation θ, the equations can be solved to obtain the associated magnetic field vectors B_y and B_x which provide the desired strength of field and orientation in each etching zone **136, 138**.

Moreover, the angular orientation and magnitude of the rotating magnetic field can be independently altered as quickly or as slowly as desired by changing the current in the electromagnets **200a-h** or by rotational movement of the magnets. The chamber controller **300** is used to vary the time that the magnetic field is at each angular position, the direction of the angular stepping function, and the field intensity. Thus the magnetic field can be stepped around the substrate **102** using selected orientation and time increments. If desired, the magnitude of the resultant field B_θ can be changed if the process conditions or chamber configuration require a constant field strength. Preferably, the magnetic field is rotated at a slow rate of 2 to 5 seconds/revolution, by sequentially changing the currents to the electromagnets **200a-h**

or rotating the permanent magnets. This steps the magnetic fields applied about the different regions **144, 146** of the substrate **102** at a slow rate and increases etch uniformity around the substrate **102**, rather than in one direction across the substrate **102**. The rotating magnetic field above the substrate **102** increases the circulation and stirring of the charged plasma species above the substrate **102**.

The variation of etch rate at the central and peripheral regions **144, 146** of the substrate **102** as a function of the strength of the magnetic field applied by the magnetic field generator **170** in an etching process is illustrated in Figure 9. The curve **197** (denoted by squares) indicates the etch rate at the peripheral region **146** for different magnetic field strengths, while the curve **198** (denoted by diamonds) indicates the etch rate at the central region **144**. In the absence of an applied magnetic field, the centrally located feature etch rates are higher than the feature etch rates at the peripheral portions of the substrate **102**. However, as the magnetic field strength is increased, at about 10 Gauss the peripheral etch rates becomes dominant over the central etch rate. At about 27 Gauss there is a local maximum in the central etch rate, and at about 42 Gauss there is a local maximum in the peripheral etch rate and also a locally maximized disparity between the central and peripheral etch rates. Good etch uniformity is provide where the two curves intersect at an applied magnetic field having a strength of about 10 Gauss. This graph demonstrates the control over the etched features **85** that may be achieved using controllable magnetic field strengths from a magnetic field generator **170**.

Alternatively, as illustrated in Figure 1g, the electromagnets **200i,j** can be arranged to provide a magnetic field that is substantially orthogonal to the plane of the substrate **102** while controlling the radial spatial density distribution of the plasma. Typically, the magnetic field generator **170** produces a magnetic field having a high strength at or outside the periphery of the substrate **102** to contain the plasma above the substrate **102**. As shown in Figure 1g, when an ion **201** attempts to leave the containment region with a radially outward velocity, the increasing magnetic field results in an ExB force that pulls the ion **201** in a circuitous path back into the containment region. The magnetic field generator **170** may comprise one or more electromagnets **200i,j** that are substantially radially symmetric about the process chamber **104**. For example, the electromagnets may be radially concentric within the same or different

planes. Currents are independently applied to the electromagnets **200i,j** by field generation power supplies **202i,j** that are independently controlled by the chamber controller **300**. These independent currents may be controlled to have varying magnitude or direction to generate a magnetic field that desirably shapes the radial spatial density distribution of the plasma.

The chamber controller **300** adjusts the power supplies **202i,j** to generate a magnetic field with a desirable vector field pattern in response to data from the process monitor **180** within a closed feedback loop. For example, the chamber controller **300** may initially generate a default magnetic field that is selected to produce a reliable plasma density distribution. The process monitor **180** transmits feedback data to the chamber controller **300** indicating processing attributes as a function of radius. The process monitor **180** may indicate that the processing attributes are occurring desirably across the substrate **102** as a function of radius, and the chamber controller **300** may respond by maintaining the magnetic field in a quiescent state. Alternatively, the process monitor **180** may indicate that the processing attributes are deviating from what has been preselected as the desired pattern, and in response the chamber controller **300** can adjust the power supplies **202i,j** to correct for the deviation.

The chamber controller **300** may compensate for past deviations from the desired state by overadjusting the magnetic field in the future to obtain an integrated attribute pattern over time that is desired. For example, when etching the substrate **102**, it may be desirable to obtain a preselected radial net etch distribution at the end of the etch process. If the process temporarily deviates from the desired distribution, the chamber controller **300** compensates in real-time by adjusting the magnetic field to temporarily produce an inverse of the desired distribution. For example, a deviation over a time interval may be corrected by an inverse deviation over the same interval, or sometimes more preferably, by a more pronounced inverse deviation over a shorter time interval, before the chamber controller **300** returns the magnetic field to the desired quiescent state.

In one exemplary embodiment, as illustrated in Figure 1g, the magnetic field generator **170** comprises two concentric electromagnets **200i,j**. According to the magnitudes and directions of the currents applied to these electromagnets **200i,j**,

different magnetic field strengths result orthogonal to the surface of the substrate **102**. Three exemplary curves of resultant magnetic field magnitudes as a function of radius across the substrate **102** are shown in Figures 8a-c for the purposes of illustration. Figure 8a shows an exemplary magnetic field magnitude that results when a current is run through the outer electromagnet **200i** while substantially no current is run through the inner electromagnet **200j**. The process gas is typically contained in the "valleys" of the curves, where the second derivative of the curve is positive. For example, in this embodiment the plasma is contained within a disc-shaped region above the central region **136** of the substrate **102**. Figure 8b shows an exemplary magnetic field magnitude that results when currents are run through both the inner and outer electromagnets **200i,j** in the same direction. Here, the plasma is contained in a thin annulus about the peripheral region **138** of the substrate **102** as well as a disc-shaped region about the central region **136** of the substrate **102**. Finally, Figure 8c shows an exemplary magnetic field magnitude that results when currents are run through the inner and outer electromagnets **200i,j** in opposite directions. In this case, the plasma is contained in a thick annulus about the peripheral region **138** of the substrate **102**. Thus, the radial density distribution of the plasma is controlled by controlling the magnetic field as a function of radius.

Returning to Figure 1b, the chamber controller **300** may adjust the gas distributor **134** and the magnetic field generator **170** in tandem to produce an overall flow pattern and radial density distribution of the plasma that is desirable. For example, the chamber controller **300** may comprise a lookup table **394**, shown in Figure 2b, that is indexed according to the gas flow rate settings and electromagnetic current settings to efficiently shape the plasma flow and distribution. The lookup table **394** may be further indexed according to a present field state of the plasma such that a desired field state of the plasma can be achieved. In one exemplary situation, it is desirable to rapidly alter the flow of the plasma from a present field state to a desired field state. Although it may be possible to control the exhaust throttle valve **163** and gas distributor **134** to eventually achieve the desired field state, the chamber controller **300** may also rapidly alter the magnetic field in the processing sector **112** to re-arrange the plasma distribution and achieve the desired field state more quickly and with reduced expenditure of process gas.

Controlling Gas Energizing Power Levels to R gulat F ature Dimensions

The chamber controller **300** also comprises program code that includes a gas energizer control instruction set **380** to control the induction field at localized process regions in the chamber **104**. For example, the gas energizer control instruction set **380** can provide instructions to the different coils **179a,b** of the antenna **174** to generate an induction field having a controllable first and second strengths about first and second regions **144, 146** of the substrate **102**, respectively. The process feedback control instruction set **388** evaluates signals from the process monitor instruction set **384**, and send instructions to the gas energizer control instruction set **380** to independently operate the coils **179a,b** of the antenna **174** to set different field strengths in relation to the signals. Each induction field strength can be independently controllable so that each may be adjusted to have a particular strength value that is needed at that region of the substrate **102**. In addition, the gas energizer control instruction set **380** may also use a process recipe that operates the antenna **174** at a single power level that generates the desired induction field strengths across the substrate **102** to provide more uniform or consistent etching of the features **85** across the substrate **102**.

The following example demonstrates the effect of the source power level of the current applied to the inductor coils **179a,b** of an antenna **174** in a DPS-type chamber illustrated in Figure 1c. Figure 10 shows the effect of different source power levels applied to the antenna on the variation in feature etch rates from the central **144** to the peripheral region **146** of the substrate **102**. Decreasing the source power reduced the variation in feature etch rates from 4500-6000 angstroms/minute at 800 Watts to 5000-5500 angstroms/minute at 550 Watts. This represented a threefold reduction in feature etch rate variation of from Δ1500 to Δ500 angstroms/minute. Thus, setting a particular or different source power levels at the central and peripheral regions **136, 138** of the substrate **102** can also be used to further enhance etching uniformity for the fine features **85** across the substrate **102**.

Controlling Substrate Zone Temperatures to R gulate Feature Proc ssing

In one version, the chamber controller operates the chamber to maintain different temperatures in the different regions of the substrate. For example, the chamber can have radiative heating elements (not shown), such as infra-red lamps or resistive wires, that are arranged in concentric circles, directly above or below the substrate support **114**. Each set of concentric lamps, or each coil of resistive wire, is separately independently powered to control the temperatures generated by them. In this manner, the chamber controller can generate different temperatures within each of the processing zones. For example, annular temperature circles can be generated within each concentric processing zone to control processing rates of the features **85** exposed to the different zones.

In one version, the support **114** has multiple temperature control zones. For example, the support **114** can have dual concentric zones that each independently receive and maintain heat transfer gas in radially inner and outer regions across the backside of the substrate **102**. For example, as illustrated in Figures 1h,i, the receiving surface **116** of the support **114** may comprise at least one gas inlet port **115** to supply heat transfer gas below the substrate **102** and at least one gas exhaust port **117** to exhaust or recycle the heat transfer gas. In the version shown in Figures 1h,i, the gas inlet port **115** comprises a plurality of inlet ports **115** concentrically arranged about the gas exhaust port **117** located at the center of the support **114**. The gas inlet ports **115** introduce heat transfer gas into the volume of space defined between the back of the substrate **102** and the receiving surface **116** of the support **114**. The gas inlet ports **115** supply a heat transfer gas such as a non-reactive gas, for example helium or nitrogen. The heat transfer gas introduced by the gas inlet ports **115** travels across the receiving surface **116** to the gas exhaust port **117** via a path of minimum hydrodynamic flow resistance.

The flow resistance along the pathway traveled by the heat transfer gas determines the difference in pressure of heat transfer gas between each of the zones **125a**, **125b** on either end of the pathway. The hydrodynamic flow resistance between the gas inlet port **115** and exhaust port **117** is controlled by providing a non-sealing protrusion **119** that is around and at least partially encircles either the gas inlet port **115**

(not shown) or the gas exhaust port **117** (as shown) to serve as a gas barrier that impedes or reduces the flow of gas between the gas inlet port **115** and the gas exhaust port **117**. The non-sealing protrusion **119** does not form an impermeable or gas-tight seal with the overlying substrate **102**. The shape of the non-sealing protrusion **119** is selected to obtain the desired hydrodynamic flow resistance across a selected portion of the receiving surface **116**.

Increased hydrodynamic flow resistance across a portion of the receiving surface **116** results in an increased gas pressure in the zone **125b** and reduced gas pressure occurs in a zone **125a**. Higher gas pressure results in higher heat transfer rates from the substrate **102** and lower gas pressure results in lower heat transfer rates. The support **114** also comprises a sealing protrusion **123** that extends around the periphery of the support **114** below the peripheral portion of the substrate **102** to contact and to form a substantially gas-tight seal with the substrate **102** to reduce leakage of the heat transfer gas into the chamber **104**. Optionally, the temperatures of the substrate backside at these two regions may also be monitored, and a thermostat (not shown) may regulate the heat transfer gas flow to achieve a desired temperature distribution across the substrate backside.

Although the present invention has been described in considerable detail with regard to certain preferred versions thereof, other versions are possible. For example, the apparatus of the present invention can be used for other chambers and for other processes, such as deposition to form the features **85** on the substrate **102**. Therefore, the appended claims should not be limited to the description of the preferred versions contained herein.